Infrared Lidar Sensitivity to Cloud Optical and Geometrical Properties:

Implications for Earth-Orbiting Doppler Lidar

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1. Introduction

Flights of calibrated backscatter lidars during the GLOBE (Global Backscatter Experiment) Pacific missions have provided the opportunity to study cloud optical properties at lidar wavelengths in the visible and near-IR (.530, 1.06, and 1.54 μm from the NASA GSFC Nd:YAG lidar) and the thermal IR (9.25 μm from the JPL CO_2 lidar), for a wide range of cloud types. These studies indicate frequent occurrence of moderate optical depth clouds and regions of sufficient porosity to permit observation of the sea surface reflectance signal and the calculation of cloud optical depth. The high horizontal spatial resolution and range-gating capability of the lidars provide a unique capability to obtain such information, which is an important ingredient in the assessment of Earth-orbiting lidar performance. The GLOBE data also provide the opportunity to study the wavelength dependence of cloud optical properties, such as backscatter and backscatter-to-extinction ratio. Several case studies of cirrus have made manifest the high observational sensitivity of lidars to thin cirrus, a sensitivity which only satellite sensors in the solar occultation mode (e.g., SAGE, ATMOS) can emulate.

The GLOBE and other airborne lidar studies, in conjunction with data from ground-based infrared lidar cloud studies, present evidence that performance of Earth-orbiting Doppler lidar in the presence of clouds must be assessed with airborne lidar data. Satellite sensors provide a wealth of data, but the coarse spatial resolution in two of the three dimensions, and the lack of vertical resolution in the middle and lower troposphere make it only marginally relevant in addressing certain issues. These include the probability of observation of backscatter signals from high cirrus and the probability of penetration to the surface.

2. Cloud Observations from GLOBE

In this paper we discuss the techniques for use of the coherent CO_2 lidar data taken in the nadir-viewing mode over the sea surface to drive various cloud optical properties at wavelengths in the thermal infrared, as well as results of JPL-Goddard Space Flight Center lidar cirrus intercomparison studies (Menzies, et al., 1992) as they pertain to assessment of Earth-orbiting Doppler lidars at 9-μm and 2-μm wavelengths.

In addition to the obvious cloud top height determination, cloud optical properties which can be obtained with a calibrated nadir viewing lidar in the 9-11 μm region include the backscatter-to-extinction ratio, which is directly related to the integrated (attenuated) backscatter (Platt and Takashima, 1987), and for clouds of moderate optical thickness at the lidar wavelength, the optical depth at the lidar wavelength and the geometric thickness. From these measured quantities the liquid water content and characteristic drop radius can be derived for each case (Chýlek, 1978; Platt and Takashima, 1987; Eberhard, 1993). The use of the sea surface reflectance signal permits calculation of the optical depth and expands the range of applicability. The use of coherent detection rather than direct detection mandates a significantly smaller field-of-view (FOV) than would normally be used in a direct detection lidar, resulting in negligible multiple scattering effects.

When the lidar is probing a single cloud layer from above, the backscatter coefficient as a function of depth is obtained, until the point is reached at which the return signal falls below the level of sensitivity of the lidar. For clouds of moderate optical thickness, the lidar signal from the surface below can be observed. Platt and Takashima (1987) show that for an optically thick cloud, whether viewing from above or below, the attenuated cloud volume backscatter coefficient, $\beta'_c(\pi, z)$, (defined as β = Ii/4 π, where B is the isotropic backscatter coefficient used in Platt and Takashima (1987)), which is the quantity measured by the lidar, is related to the backscatter-to-extinction ratio. The attenuated cloud volume backscatter coefficient can be defined as

$$\beta'_c(\pi,z) = \beta_c(\pi,z)\exp\left[-2\int_{z_t}^{z} \eta(z')\sigma_c(z')dz'\right] \tag{1}$$

where $\beta_{c(\pi,z)}$ is the unattenuated volume backscatter coefficient, UC(Z) is the volume extinction' coefficient, $\eta(z)$ is a multiple scattering factor, and z_t is the cloud top. (It is assumed that the lidar is above the cloud, sounding vertically downward, as in Platt, et al.,(1989).) Platt and Takashima point out that if the backscatter to extinction ratio,

$$k = \beta_c(\pi,z) / \sigma_c(z) \tag{2}$$

and the multiple scattering factor, q(z), are assumed constant through the probed region of the cloud, then the integral of $\beta'_c(\pi,z)$, which is the integrated attenuated backscatter, $\gamma'(\pi)$, can be expressed as

$$\gamma(\pi) = (k/2\eta)\left\{1 - \exp\left[-2\eta\delta_c\right]\right\} \qquad (3)$$

i.e., the integrated attenuated backscatter, which is a lidar observable, can be expressed in terms of the backscatter-to-extinction ratio, the multiple scattering factor, and the cloud optical depth, SC, at the lidar wavelength. For clouds of small to moderate optical thickness a direct measurement of optical depth, δ_c, can be made by using the "clear atmosphere" sea surface signal in the neighborhood of the clouds as a reference intensity. It has been determined from analysis of ABL data taken in a nadir-viewing mode over the Pacific that the sea surface signal is relatively steady over flight track lengths which are long compared with spatial scales of variability of many cloud types. The multiple scattering factor for the JPL airborne coherent CO_2 lidar is unity, since multiple scattering contributions to the signal are extremely small.

Case studies of the retrieval of cloud optical depth and backscatter-to-extinction ratio will be presented.

JPL and GSFC investigators have intercompared a number of cirrus observations from the GLOBE missions (Menzies, et al., 1992). For each case studied the plotted backscatter ratios $\beta(1.06\text{-}\mu m)/\beta(9.25\text{-}\mu m)$ indicate a mean value which is consistent over a dynamic range of at least three orders of magnitude. These mean values range from 50 to 100 for the various cases. (The square of the wavelength ratio is 76.) The high values for the backscatter ratio are due in part to the strong absorption at 9.25-pm.

3. Implications for Earth-Orbiting Doppler Lidar

The use of either 9-pm or 2-pm wavelengths for an Earth-orbiting Doppler lidar such as LAWS (Laser Atmospheric Wind Sounder) will provide unprecedented sensitivity to optically thin clouds and small cloud cells with diameters of a few hundred meters or less. The sensitivities of airborne and Earth-orbiting infrared- lidars to cloud properties depends strongly on wavelength and the EAP/R^2 (the lidar Energy-Aperture Product divided by the square of the Range to the cloud), as well as the FOV (field-of-view of the lidar) and the nadir angle. For example, at the 9-μm wavelength the backscatter sensitivity threshold value for EAP values in the neighborhood of 1 Jm^2 would be near $10^{-9} m^{-1} sr^{-1}$. Since typical extinction-to-backscatter ratios for cirrus are in the 400-2000 sr range, this sensitivity would permit the detection of very thin cirrus with extinction coefficients as low as 4 x $10^{-4} km^{-1}$. Since the extinction-to-backscatter ratio at 2-μm for ice clouds is expected to be near a value of 30 sr (and not as dependent on the cloud microphysics as at the 9-pm wavelength), the shorter wavelength provides even more sensitivity to ice particles.

Satellite sensors in a (near) nadir viewing mode, with spatial resolutions ranging from l-km to 8-km, do not recognize high clouds unless the absorption emittance, averaged over a pixel, is typically greater than 0.05 ((Wielicki and Parker, 1992), which limits sensitivity to thin clouds or small cloud cells. The treatment of multilayered cloud systems in the retrieval of cloud properties from satellite data is also problematical. SAGE is much more sensitive to cirrus than the other satellite sensors, since it is viewing the limb in a solar occultation mode, SAGE can detect extinction coefficients as low as $10^{-4} km^{-1}$, for absorbers (or scatterers) which are uniformly distributed over horizontal spatial scales of 100 km or more (McCormick, et al, 1979). However the long limb viewing paths and the sparse sampling capability of the solar occultation technique present data interpretation difficulties, although the SAGE data have been used for many years to develop cirrus climatologies on seasonal temporal scales (Woodbury and McCormick, 1983).

Acknowledgements

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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